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Optimization of Coal Beneficiation Plants for SO2 Emissions Control

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16. ABSTRACT The article describes an optimization model for estimating the properties and cost of washed coal from coal beneficiation plants of varying levels of complexity. The design and technical description of the plant performance model are presented, together with cost algorithms for three plant designs with increasing sulfur removal capability. Important concepts included in the model are the treatment of different coal size fractions, the efficiency of coal washing equipment, and the optimization of plant yield to achieve a target coal quality. When employed in a larger simulation framework, the plant model serves as a building block for obtaining more realistic estimates of the role of coal cleaning as a cost-effective method of sulfur emissions reduction from coal combustion.

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Optimization of Coal Beneficiation Plants for SO_2 Emissions Control

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An optimization model for estimating the properties and cost of washed coal from coal beneficiation plants of varying levels of complexity is described. The design and technical description of the plant performance model is presented, together with cost algorithms for three plant designs with increasing sulfur removal capability. Important concepts included in the model are the treatment of different coal size fractions, the "efficiency" of coal washing equipment, and the optimization of plant yield to achieve a target coal quality. When employed in a larger simulation framework, the plant model serves as a building block for obtaining more realistic estimates of the role of coal cleaning as a cost-effective method of sulfur emissions reduction from coal combustion.

In recent years, concern over the acid rain issue has increased the national and international interest in sulfur removal technologies suitable for coal-fired power plants and industrial boilers. While much of this attention has focused on post-combustion desulfurization processes, the potential role of physical coal cleaning also has received considerable interest. Physical coal cleaning is a mature technology which combines a number of individual processes to enhance the quality of run-of-mine coal. In the U.S., coal preparation for steam coals has become common as the degree of mechanization in coal mines has increased, bringing higher proportions of fine sizes and impurities in the mined product. Traditionally, the primary objectives of coal preparation have been to achieve a greater degree of uniformity of coal particle size, and to reduce ash content to acceptable levels, thereby also reducing transportation costs. However, physical coal cleaning also can reduce the sulfur content of coal by removing pyritic sulfur, which takes the form of discrete particles. Organic sulfur, which forms an integral part of the coal matrix, and may comprise 30–70 percent of the total sulfur content, can be removed only by chemical processing.

This paper describes a newly developed analytical model of conventional coal cleaning plants, designed to estimate the cost and capability of coal cleaning for removing sulfur to help meet air pollution emission standards. The model has relatively few detailed data requirements, in contrast to very detailed design models of preparation plants such as that developed by Gottfried.[1] Nevertheless, it incorporates three important concepts related to coal preparation plant operation, namely, the treatment of different size fractions, the "efficiency" of coal washing equipment, and the optimization of plant yield while meeting a target coal quality. This provides more realistic estimates of coal cleaning capability than heretofor available for use in large-scale utility and coal market models.[2] The model is implemented in a Fortran computer program used later in the paper to present illustrative results.

Coal Preparation Processes

Many different types of processes are used for washing coal, including jigs, concentrating tables, dense medium vessels, cyclones, and froth flotation devices. The operation of these devices are comprehensively described in the literature.[3–6] Process selection depends on the size of coal to be washed and the extent to which coal qualities are to be enhanced. In operation, all of these processes (apart from froth flotation) may be characterized by a "specific gravity of separation." Coal particles of higher density, which tend to have higher concentrations of ash and pyritic sulfur, are discarded as refuse while the product coal (the "float") consists of the lighter particles.

Washing does not produce an ideal separation between particles heavier and lighter than the characteristic specific gravity of separation. Thus, the performance of a washing plant may be described by "partition" or "distribution" curves of the type shown in Figure 1. This diagram shows that some light particles report to the refuse while some heavy particles report to the float. There are several differ-

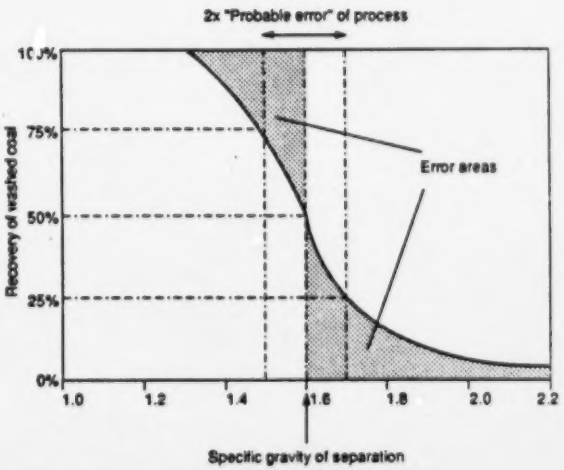

Figure 1. "Partition" curve for coal washing in a Baum jig.

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ent measures related to the amount of misplaced material associated with the washing process. The "error area" indicated in Figure 1, is one such measure. Another is the "probable error," defined as half the specific gravity interval spanned by the partition curve in passing from 25 to 75 percent recovery.[6] Typical probable errors for different types of washing equipment are shown in Table I.

Table I. Typical probable errors for various types of coal washing equipment.[6]

Type of equipment	Probable error (specific gravity)
Jigs	±0.10
Concentrating tables	±0.09
Hydrocyclones	±0.09
Heavy medium cyclones	±0.03
Heavy medium vessels	±0.035

Coal preparation plants operate by screening coal into several streams differentiated with respect to coal size. Each of these streams may be treated in a different manner. For the purposes of this model, three generic levels of preparation plants are identified.[3,4] A summary of the processes associated with each of these levels is shown in Table II.

Table II. Model preparation plant processes (in addition to crushing and screening).[3,4]

Preparation level[a]	Top sizes	Mid sizes	Fine sizes
2	Heavy medium cyclone	No cleaning	No cleaning
3	Heavy medium vessel	Heavy medium cyclone (drying optional)	No cleaning
4	Heavy medium vessel	Heavy medium cyclone (drying optional)	Hydrocyclone drying

[a] Preparation Level 1 simply involves crushing and screening, with no sulfur removal.

Generally, a preparation plant will be designed to produce coal of a certain target quality at a minimum cost. Cost will be minimized when the overall yield of the plant, defined as the ratio of plant input to output (either on a weight or energy content basis), is maximized. By balancing the specific gravities of separation, and hence, the yields for the different preparation streams, it is possible to optimize the overall plant yield while meeting a required quality target.

The operational details of a preparation plant depend upon the washability characteristics of the coal to be cleaned. An example of washability data is shown in Table III for three cumulative size fractions unadjusted for the "efficiency" of washing equipment. Coal characteristics are expressed on a dry basis, which provides a stable and consistent basis for characterizing a coal whose moisture content may vary considerably during the preparation process. As the specific gravity of separation increases so does the recovery of coal, though with a lowering of coal quality. Thus, there is an inherent tradeoff between coal quality and coal recovery.

Plant Performance Model

A schematic of the model procedures is shown in Figure 2. Washability data may come in a variety of forms; therefore, the first step is to manipulate the raw data into a form which represents the washability of the coal streams in the particular plant being modeled. The second step is to adjust the washability data to take account of the efficiency of washing equipment as represented by the "probable error" in the specific gravity of separation. Given a target for either the ash or sulfur content of the final coal, the Lagrange multiplier technique is used to calculate the plant design which will result in the maximum overall recovery of coal. The model identifies the value of the Lagrange multiplier which results in the optimal operating characteristics and uses it to derive the properties of the washed coal and the process yield for each coal stream. Table IV defines all the symbols used for the analytical model.

Estimating Size Distributions

Size distribution data are needed for manipulating the washability data and for determining the maximum recovery of coal. In the absence of coal-specific data, this distribution is obtained from the Rosin and Rammler equation, which describes the size distribution resulting from breaking or crushing many brittle materials[8]:

$$F(X) = \exp[-(X/X_0)^a] \quad (1)$$

Molburg[9] analyzed the size distribution data for 19 coals to estimate relationships for X_0 and a:

$$X_0 = 0.433X_t \quad (2)$$

$$a = 0.4 + X_t \quad (3)$$

Adjusting Washability Data for Stream Size

Algorithms for determining plant yield generally require noncumulative washability data for each wash stream. For example, a particular coal cleaning plant may wash three size fractions of coal, e.g., 2.0″ × 0.25″, 0.25″ × 28 mesh (0.0232″), and 28 mesh × 0. Often, however, washability data are not available in this form. For example, the comprehensive database of the U.S. Bureau of Mines (USBM)[7] gives cumulative data for the size ranges 1.5″ × 0″, 0.375″ × 0, and 14 mesh (0.0464″) × 0. The present model converts such data into non-cumulative form for each plant stream. For cumulative data corresponding to topsizes X and W, coal quality and yield for a stream of sizes between X and W are given by:

$$q_s(X,W) = \frac{Y_s(X)q_s(X)F^u(X) - Y_s(W)q_s(W)F^u(W)}{Y_s(X)F^u(X) - Y_s(W)F^u(W)} \quad (4)$$

and

$$Y_s(X,W) = \frac{Y_s(X)F^u(X) - Y_s(W)F^u(W)}{F^u(X) - F^u(W)} \quad (5)$$

where F^u comes from Equation 1. If the cumulative washability data do not correspond to plant wash stream top and bottom sizes, a logarithmic interpolation is recommended. Thus, if Z is the desired size, and X and W are the nearest sizes for the data available:

$$q_s(Z) = \frac{q_s(W) - q_s(X)}{\ln W - \ln X}[\ln Z - \ln X] + q_s(X) \quad (6)$$

$$Y_s(Z) = \frac{Y_s(W) - Y_s(X)}{\ln W - \ln X}[\ln Z - \ln X] + Y_s(X) \quad (7)$$

Some washability data also do not contain the higher heating value of cleaned coal for each specific gravity category. This can be estimated by:

$$q_s^{Btu} = H_R\left(\frac{1 - q_s^{Ash}}{1 - A_R}\right) \quad (8)$$

An adjustment also is needed if energy recovery rather than mass recovery is to be maximized. Using the coal heating value, weight recovery data are converted to Btu recov-

Table III. Example of USBM coal washability data.[7]

Properties	Specific gravity categories			
	<1.3	<1.4	<1.6	<2.2
Size range 1.5" × 0"				
Yield (%)	64.10	78.40	87.00	100.00
Ash (%)	8.40	8.90	9.90	15.40
Sulfur (%)	2.22	2.45	2.91	5.23
HHV (Btu/lb)	12,831	12,762	12,622	11,855
Size range 0.375" × 0"				
Yield (%)	51.50	77.70	85.70	100.00
Ash (%)	5.80	7.20	8.20	15.10
Sulfur (%)	1.96	2.12	2.50	5.31
HHV (Btu/lb)	13,194	12,999	12,859	11,897
Size range 0.0464" × 0"				
Yield (%)	37.20	70.00	84.20	100.00
Ash (%)	5.10	6.60	8.20	15.60
Sulfur (%)	1.94	2.21	2.48	5.35
HHV (Btu/lb)	13,292	13,083	12,859	11,827

ery data, and the various coal qualities are normalized with respect to energy content.

Adjustment for Washer Efficiency

Washability data are adjusted for washer efficiency using the partition curve for a particular process at a given specific gravity of separation. This may be described by the functional form $r = r_f(g)$, where $r_f(g)$ is the fraction of coal of specific gravity g reporting to the "float," i.e., the cleaned coal product stream. If $f(g)dg$ is the fraction of the raw coal with specific gravity lying between g and $g + dg$, then the adjusted yield for the process is:

$$Y_{s,e} = \int_0^\infty r_f(g)f(g)dg \tag{9}$$

Similarly, if $q_s dg$ is the "quality" (i.e., sulfur, ash or energy content) per pound of cleaned coal with specific gravity between g and $g + dg$, then $r_f(g)f(g)q_s dg$ is the quality per pound of raw coal within that specific gravity interval. Then, the adjusted quality fraction of the clean coal is given by:

$$q_{s,e} = \frac{\int_0^\infty r_f(g)f(g)q_s(g)dg}{\int_0^\infty r_f(g)f(g)dg} = \frac{\int_0^\infty r_f(g)f(g)q_s(g)dg}{Y_{s,e}} \tag{10}$$

Defining the specific gravity for a base yield of zero as g_0, and for a yield of 1.0 as g_{max}, Equation (9) can be rewritten as:

$$Y_{s,e} = \int_{g_0}^{g_s} r_f(g)f(g)dg + \int_{g_s}^{g_{max}} r_f(g)f(g)dg \tag{11}$$

where g_0 is estimated from the available specific gravity categories, and g_{max} is typically 2.2.[10] Within a particular specific gravity range, $f(g)$ is assumed to be constant, and is estimated from the washability data as:

$$f(g) = \frac{Y_{s+1} - Y_s}{g_{s+1} - g_s}. \tag{12}$$

In a similar way, $q_s(g)$ is assumed to be a piecewise linear function, and $r(g)$ is assumed to be dependent only on the type of washing equipment and to have a piecewise linear form approximating the true partition curve (Figure 1). Therefore, $r(g)$ is completely defined by a specific gravity of separation and a "probable error" for the washing process.

Figure 3 shows a plot of the reduction in sulfur content of a washed coal as a function of the mass yield at various values of probable error. These curves are derived by applying Equations 10 and 11 to a washability curve for a typical Pennsylvania coal. The results are in good agreement with the actual performance of coal cleaning plants. Noting the probable errors indicated in Table I, it is apparent that for some equipment, notably jigs, concentrating tables, and hydrocyclones, the effects of washing inefficiency can be significant as process yields are reduced to achieve higher sulfur reductions.

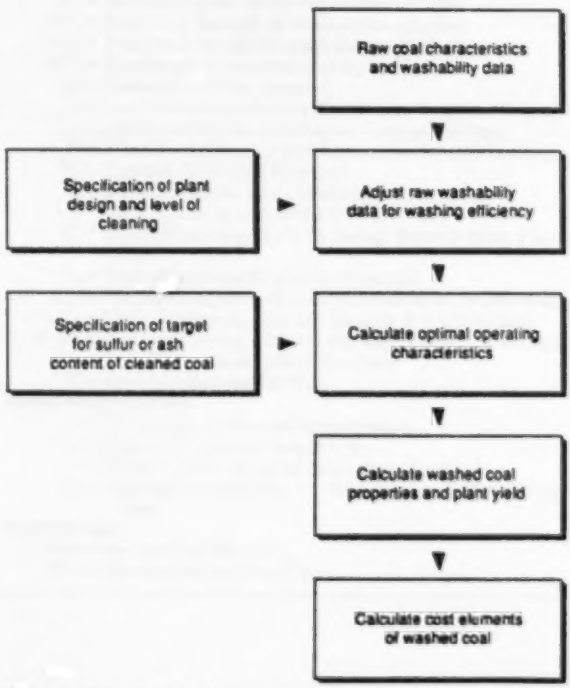
Raw coal characteristics and washability data
Specification of plant design and level of cleaning
Adjust raw washability data for washing efficiency
Specification of target for sulfur or ash content of cleaned coal
Calculate optimal operating characteristics
Calculate washed coal properties and plant yield
Calculate cost elements of washed coal

Figure 2. Schematic of model procedures.

Optimizing Plant Operation

The Lagrange multiplier technique is used to maximize either the mass or energy yield of the coal cleaning plant. This technique rests on the assumption that for any particular washing process, the washed coal quality may be described as a function of the process yield. Thus, $q = q(Y)$. The technique is developed for a model coal washing system in which the coal quality in each wash stream is described by a piecewise linear function dependent upon specific gravity.

Table IV. Nomenclature for model equations.

English letter symbols

- a = Parameter for size distribution function (dimensionless)
- A_R = Ash content of raw coal (dry wt. fraction)
- $C_{Capital}$ = Total capital cost ($/dry ton of cleaned coal)
- C_{chem} = Annual cost of chemicals ($/dry ton of cleaned coal)
- C_{elect} = Annual cost of electricity ($/dry ton of cleaned coal)
- c_i = Chemical cost for ith level plant ($/dry ton of raw coal)
- C_{idx} = Annual cost escalation-index (dimensionless)
- C_{labor} = Annual cost of labor ($/dry ton of cleaned coal)
- C_{maint} = Annual cost of maintenance ($/dry ton of cleaned coal)
- $C_{Operating}$ = Total operating cost ($/dry ton of cleaned coal)
- C_{payovh} = Annual cost of payroll overhead ($/dry ton of cleaned coal)
- C_{pltovh} = Annual cost of plant overhead ($/dry ton of cleaned coal)
- C_{Raw} = Cost of raw coal ($/dry ton)
- C_{Refuse} = Cost of refuse coal ($/dry ton of cleaned coal)
- C_{tax} = Annual cost of taxes, insurance, etc. ($/dry ton of cleaned coal)
- C_{Total} = Total cost of cleaned coal ($/dry ton)
- C_{waste} = Annual cost of waste disposal ($/dry ton of cleaned coal)
- C_{water} = Annual cost of water ($/dry ton of cleaned coal)
- CRF = Capital recovery factor (fraction)
- d = Real discount rate (fraction)
- DC_{clean} = Direct capital cost for cleaning equipment ($)
- DC_{raw} = Direct capital cost for raw coal handling ($)
- DC_{refuse} = Direct capital cost for refuse handling ($)
- DC_{sample} = Direct capital cost for coal sampling system ($)
- $DC_{thermal}$ = Direct capital cost for thermal drying system ($)
- e_i = Cost of electricity for ith level plant ($/dry ton of raw coal)
- E_d = Energy needed for thermal drier (Btu/lb of dry coal)
- f_d = Fraction of the cleaned coal to be thermally dried
- f_i = Weight or Btu fraction of wash stream, i
- $f(g)$ = Fraction of coal at specific gravity, g
- $F(X,W)$ = Fraction of coal greater than size X and less than size W
- $F^0(X)$ = Fraction of coal greater than size X
- $F^w(X)$ = Fraction of coal less than size X
- g = Specific gravity of a wash circuit (dimensionless)
- g_{max} = Specific gravity at 100% yield (dimensionless)
- g_0 = Specific gravity at 0% yield (dimensionless)
- g_s = Specific gravity at category, s (dimensionless)
- h = Annual hours of cleaning plant operation (h/yr)
- H_0 = Higher heating value of washed coal (Btu/dry lb)
- H_R = Higher heating value of raw coal (Btu/dry lb)
- i = Nominal interest rate (fraction)
- ICF = Indirect charge factor (fraction)
- IDC = Indirect capital cost ($)
- LHV = Lower heating value of washed coal (Btu/dry lb)
- l_i = Total labor cost for ith level plant ($/h)
- k_i = Cost coefficient for cleaning equipment ($/dry ton of raw coal)
- m_i = Maintenance cost for ith level plant (fraction of TCC)
- m = Characteristic coal flow rate (dry tons/h)
- m' = Weight of water evaporated per pound of dry coal processed (fraction)
- m'_i = Moisture content of coal entering thermal drier (fraction)
- m'_0 = Moisture content of coal leaving thermal drier (fraction)
- m'_r = Mass flow rate of water evaporated in thermal drier (tons/h)
- m_{dry} = Mass flow rate of coal entering thermal drier (dry tons/h)
- m_0 = Mass flow rate of cleaned coal out of plant (dry tons/h)
- m_r = Mass flow rate of raw coal into plant (dry tons/h)
- m_{ref} = Dry mass flow rate of refuse coal (tons/h)
- m_{ref}^w = Wet mass flow rate of refuse coal (tons/h)
- n = Life of coal cleaning plant (years)
- p = Inflation rate (fraction)
- p = Coal quality (ash, sulfur or HHV per unit energy or dry mass)
- q_i = Coal quality for stream, i (ash, sulfur or HHV)
- $q_{i,r}$ = Coal quality for wash stream, i in range, r
- q_s = Coal quality in specific gravity category, s
- $q_{s,s}$ = Coal quality in category, s adjusted for probable error
- $q_s(X)$ = Coal quality for size fraction $X \times 0$ in category, s
- $q_s(X,W)$ = Coal quality of coal for size fraction $X \times W$ in category, s
- Q^* = Targeted clean coal quality (ash or sulfur per energy or unit dry mass)
- r = Index for specific gravity ranges (integer)
- $r_f(g)$ = Fraction of material in the float at specific gravity, g
- s = Specific gravity category (integer)
- S_R = Sulfur content of raw coal (dry wt. fraction)
- t_i = Taxes and insurance costs for ith level plant (fraction of TCC)
- TCC = Total capital cost ($)
- TDC = Total direct cost ($)
- w_i = Cost of water for ith level plant ($/dry ton of raw coal)
- W = Arbitrary coal size (inches)
- W_c = Working capital ($/dry ton of cleaned coal)
- WS_b = Topsize of the bottom wash stream (inches)
- WS_m = Topsize of the middle wash stream (inches)
- WS_t = Topsize of the top wash stream (inches)
- X = Arbitrary coal size (inches)
- X_t = Coal top size used in size distribution function (inches)
- X_0 = Parameter for size distribution function (inches)
- Y = Yield (output/input) based on mass or energy (fraction)
- Y_d = Thermal drier yield (fraction)
- Y_i = Yield of wash stream, i (fraction)
- $Y_{i,s}$ = Yield of stream, i, in category, s (fraction)
- Y_p = Yield of cleaning plant excluding thermal drier (fraction)
- Y_s = Yield at any specific gravity (fraction)
- $Y_{s,s}$ = Yield in category s adjusted for probable error (fraction)
- $Y_s(X)$ = Yield in category, s for size fraction $X \times 0$ (fraction)
- $Y_s(X,W)$ = Yield in category, s for size fraction $X \times W$ (fraction)
- Y_t = Y for total cleaning plant (fraction)
- Z = Arbitrary coal size (inches)

Greek letter symbols

- α = Y-intercept of the quality function, $q_{i,r}$
- $\beta_{i,r}$ = Slope of the quality function, $q_{i,r}$
- ϵ = Thermal efficiency of thermal drier (fraction)
- λ_i = Lagrangian multiplier for wash stream, i (dimensionless)

Superscripts

- Ash = Ash quality value of q_s
- Btu = Energy quality value of q_s

Suppose there are N washed streams denoted by the index i, and M specific gravity ranges denoted by the index r. For each specific gravity range, $q(y)$ then can be described as:

$$q_{i,r} = \alpha_{i,r} + \beta_{i,r} Y_i \tag{13}$$

where

$$\alpha_{i,r} = \frac{q_{i,s} Y_{i,s+1} - q_{i,s+1} Y_{i,s}}{Y_{i,s+1} - Y_{i,s}} \tag{14}$$

and

$$\beta_{i,r} = \frac{q_{i,s+1} - q_{i,s}}{Y_{i,s+1} - Y_{i,s}} \tag{15}$$

Suppose also that the fraction of raw coal (measured by weight or energy content) associated with stream i is f_i, such that

$$\sum_{i=1}^{N} f_i = 1. \tag{16}$$

Then, the overall plant yield is:

$$Y_p = \sum_{i=1}^{N} f_i Y_i \tag{17}$$

The quality of the washed coal is then given by:

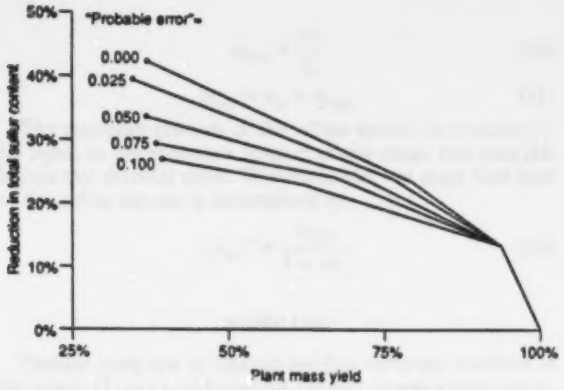

Figure 3. Effect of probable error in sulfur reduction for a typical Pennsylvania coal.

$$Q = \frac{\sum_i f_i Y_i q_{i,r}}{\sum_i f_i Y_i} = Q^* \tag{18}$$

where Q^* is the target quality. Thus, we wish to maximize the yield, Equation 17, subject to the constraint, Equation 18. The latter can be rewritten as:

$$\sum_i f_i Y_i (q_{i,r} - Q^*) = 0 \tag{19}$$

Using the Lagrange multiplier technique for optimization subject to constraints,[11] it can be shown that the following equation must be satisfied for each wash stream:

$$f_i + \lambda f_i \left(Q^* - q_{i,r} - Y \frac{\partial q_{i,r}}{\partial Y_i} \right) = 0 \tag{20}$$

where λ_i is the undetermined Lagrange multiplier. Simplifying and rearranging gives:

$$q_{i,r} + Y_i \frac{\partial q_{i,r}}{\partial Y_i} = Q^* - \frac{1}{\lambda_i} \tag{21}$$

Using Equation 13, it is possible to solve for the Lagrange multipliers and optimal coal quality values in each specific gravity category and wash stream which satisfy the constraint equation while maximizing overall yield. Then, the values of optimal yield and final clean coal properties can be determined from the washability data. Because the model functions are discontinuous, however, an iterative solution is necessary. One subroutine of the computer program sets up the left-hand sides of Equation 21, while another searches the linear segments of these functions for an optimal solution, starting at the ends of the functions representing the highest recoveries of coal. A detailed derivation and numerical example are given in Reference 10. A solution which would involve a process yield less than that covered by the available data is considered infeasible. It is assumed that any coal quality target which would involve such low yields cannot be met.

Economic Model

The cost of coal cleaning plants is known to be highly variable and site-speific, with relatively little systematic data available for actual operating facilities. Cost estimates, therefore, are generally based on conceptual engineering designs for new facilities of different levels of complexity. In this study, economic models for coal preparation plants have been developed for three typical plant configurations (Levels 2, 3, and 4) based on other detailed studies.[3-5,12]

The total cost per dry ton of cleaned coal is divided into four separate items: (1) the cost of raw coal, (2) the cost of rejected coal (lost with the refuse), (3) annual plant variable costs, and (4) annual plant fixed costs. The cost of raw coal is assumed to be an input parameter to the model. In some cases this may reflect the cost of a "basic" level of preparation (such as simple crushing and screening) normally used to produce a saleable product. A method for incorporating this in estimates of regional coal washability is discussed in Reference 13. The cost of rejected coal is then a function of the plant yield:

$$C_{Refuse} = C_{Raw} \left(\frac{1}{Y_t} - 1 \right) \tag{22}$$

Estimates of plant capital and operating costs typically are scaled to various mass flow rates within the plant. The key rates used here are the raw coal feed into the plant, the rates of dry and wet refuse coal out of the plant, and the rate of water evaporated in the thermal drier.

Normally, it is necessary to thermally dry the fine sizes of washed coal, which accumulate large quantities of moisture during the washing process. Sometimes it may also be necessary to thermally dry the midsizes. In the computer model, it is possible for the user to specify which streams are to be dried. Therefore, the fraction of coal which is thermally dried is:

$$f_d = \frac{\sum_i f_i Y_i}{Y_p} \tag{23}$$

where i are the streams to be dried.

It is assumed that product coal is used to fire the thermal drier, thus reducing the overall plant yield. It is also assumed that drying alters only the coal moisture content, with all the other coal properties remaining the same on a dry basis. Since the moisture content of coal entering and leaving the thermal drier is specified, the weight of the water evaporated per pound of dry coal into the thermal drier is:

$$m' = \frac{f_d (m'_i - m'_0)}{(1 - m'_i)(1 - m'_0)} \tag{24}$$

The amount of energy needed to evaporate this water is:

$$E_d = \frac{1020 m'}{\epsilon} \tag{25}$$

where 1020 Btu/lb is the heat of vaporization. An approximation for the lower heating value of coal is:

$$\text{LHV} = 0.96 H_0 - \frac{1020\, m'_0}{1 - m'_0} \tag{26}$$

where the factor 0.96 allows for the energy required to evaporate the water formed from the hydrogen content of coal, and the second term allows for the energy needed to evaporate coal moisture. Using Equations 25 and 26, the thermal drier yield can be expressed as:

$$Y_d = 1 - \frac{E_d}{LHV} \tag{27}$$

where the second term represents the fraction of cleaned coal required to fire the thermal drier. The total plant yield is then given by:

$$Y_t = Y_d Y_p \tag{28}$$

Once the drier yield is determined, the dry mass flow rates for the raw coal stream, refuse stream, and drier stream also can be calculated:

$$m_r = \frac{m_0}{Y_t} \tag{29}$$

$$m_{dry} = \frac{m_0}{Y_d} \quad (30)$$

$$m_{ref} = m_r - m_{dry} \quad (31)$$

The moisture content of the refuse stream is assumed to be equal to the moisture content of the clean coal streams before the thermal drier. Therefore, the wet mass flow rate of the refuse stream is determined by:

$$m_{ref}^{w} = \frac{m_{ref}}{1 - m'_i} \quad (32)$$

Capital Cost

Capital costs are estimated for five different sections of the plant: (1) raw coal handling, (2) coal cleaning equipment, (3) thermal drying, (4) refuse handling, and (5) coal sampling system. The direct capital costs of each section other than the coal sampling system is related to its characteristic mass flow, and is assumed to have an economy of scale of 0.7 for plant sizes in the range of 500 to 2000 clean tons per hour (tph).[3] Therefore, for these sections the direct cost equation has the form:

$$DC = km^{0.7} \quad (33)$$

where k is a constant and m is a characteristic flow rate. Only the cost of the cleaning equipment section is assumed to vary with different plant levels. The capital cost related to clean coal handling is included in the raw coal handling cost since the cleaning plant is assumed to be at the mine site. This includes the cost of conveyors, storage, and loading equipment. It is assumed that the cost of the coal sampling system does not vary with plant capacity.

All direct equipment costs are first estimated in 1978 dollars based on costs for plant of different levels of complexity reported in recent studies[3,12]:

$$DC_{raw} = 12{,}800\, m_r^{0.7} \quad (34)$$

$$DC_{clean} = k_i m_r^{0.7} \text{ where,} \quad (35)$$

$$k_2 = 20{,}700 \text{ (Level 2)} \quad (35a)$$

$$k_3 = 35{,}800 \text{ (Level 3)} \quad (35b)$$

$$k_4 = 45{,}500 \text{ (Level 4)} \quad (35c)$$

$$DC_{thermal} = 128{,}000\, (m'_e)^{0.7} \quad (36)$$

$$DC_{refuse} = 31{,}400\, m_{ref}^{0.7} \quad (37)$$

$$DC_{sample} = 324{,}000 \quad (38)$$

The total direct capital cost is found by adding Equations 34 through 38:

$$TDC = DC_{raw} + DC_{clean} + DC_{thermal} + DC_{refuse} + DC_{sample} \quad (39)$$

Indirect capital costs include engineering costs, construction and field expenses, and contractor's fees. Each of these is nominally estimated to be 10 percent of the total direct cost.[12] Contingencies are nominally estimated to be 25 percent of the direct plus indirect capital cost, and includes allowance for start-up and performance tests.[12] Therefore, the total capital cost to be depreciated over the life of the plant nominally is:

$$TCC = 1.625(TDC) \quad (40)$$

Other assumptions regarding indirect cost fractions, contingencies, etc. can be accommodated in the computer model by specifying other values of the total indirect cost factor, ICF. Thus, the more general expression for total capital cost is,

$$TCC = (ICF)(TDC) \quad (41)$$

The total capital cost is annualized in constant dollars using the real discount rate:

$$d = \frac{1+i}{1+p} - 1 \quad (42)$$

The capital recover factor is then given as:

$$CRF = \frac{d}{1 - (1+d)^{-n}} \quad (43)$$

Working capital is estimated to be 25% of the labor, maintenance, electricity, water, waste disposal, and chemicals costs [12]:

$$W_c = 0.25(C_{labor} + C_{maint} + C_{elect} + C_{water} + C_{waste} + C_{chem}) \quad (44)$$

The annual charges associated with working capital is estimated to be the real interest rate, d, times the working capital (expressed here in dollars per clean ton). The total capital cost in dollars per dry ton of cleaned coal, escalated to a current year basis via a construction cost index, then is:

$$C_{capital} = \left(dW_c + \frac{(TCC)(CRF)}{m_0 h}\right) c_{idx} \quad (45)$$

Operating and Maintenance Costs

Annual operating and maintenance costs include labor, maintenance, raw materials, and waste disposal costs, as well as taxes, insurance, and general administrative overhead. Based on a detailed analysis of the costs of preparation plants of various designs, representative cost factors for each of the three generic plant levels were derived by Onursal, *et al.*[12] These are shown in Table V. It should be noted that the cost factors relate to a number of different attributes of preparation plant operation. A comparison of reports by Bechtel[3] and Versar[12] revealed that labor costs were insensitive to plant throughput over a range of 400–1000 ton/h. Therefore, they were related only to hours of plant operation. The cost per hour of plant operation is based on two shifts per day, 250 days/year. Maintenance costs were taken to be proportional to the total capital cost of the plant. The cost of electricity, water, and chemicals were linked to the mass rate of coal entering the plant, while the cost of waste disposal was assumed to be proportional to the quantity of coal rejected. Overhead costs based on labor, maintenance and materials are a significant additional expense. The total plant operating and maintenance cost is then composed of the following items:

$$C_{labor} = \frac{l_i}{m_0} \quad (46)$$

$$C_{maint} = \frac{m_i(TCC)}{m_0 h} \quad (47)$$

$$C_{chem} = \frac{c_i}{Y_t} \quad (48)$$

$$C_{elect} = \frac{e_i}{Y_t} \quad (49)$$

Table V. Preparation plant operating cost factors.[a]

Variable cost element	Preparation plant level 2	3	4
Chemicals, c_i ($/raw ton)	0.025	0.044	0.070
Electricity, e_i ($/raw ton)	0.065	0.134	0.152
Labor, l_i ($/h)	132.00	138.00	225.00
Maintenance, m_i (fraction TCC)	0.07	0.07	0.07
Refuse disposal, r_i ($/wet ton)	1.00	1.00	1.00
Taxes, t_i (fraction TCC)	0.04	0.04	0.04
Water, w_i ($/raw ton)	0.0011	0.0018	0.0020

[a] All costs in 1978 dollars.[12]

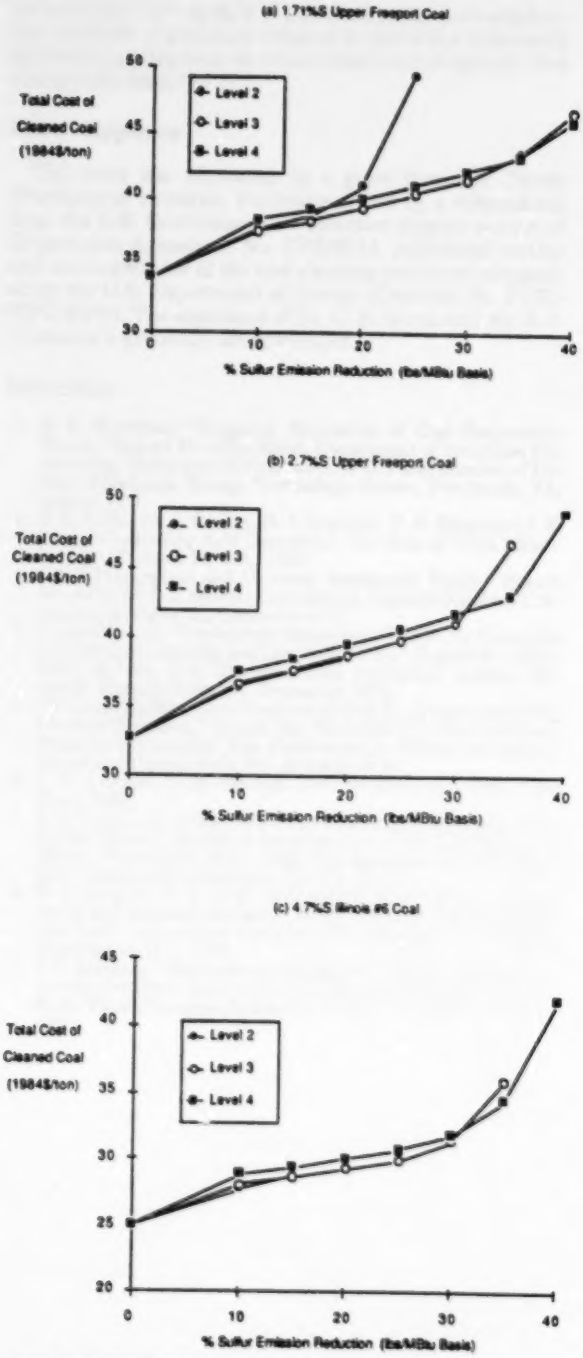

Figure 4. Predicted sulfur reduction costs for three U.S. coals.

$$C_{water} = \frac{w_i}{Y_t} \tag{50}$$

$$C_{waste} = \frac{r_i m_{ref}''}{m_0} \tag{51}$$

$$C_{payovh} = 0.30 C_{labor} \tag{52}$$

$$C_{pltovh} = 0.26(C_{labor} + C_{maint} + C_{chem}) \tag{53}$$

Nominal values of c_i, e_i, l_i, m_i, r_i, and w_i are shown in Table V. In addition, annual taxes, insurance, etc. are expressed as a fraction of total capital cost:

$$C_{tax} = \frac{t_i(TCC)}{m_0 h} \tag{54}$$

Adding the above equations and converting to a current base year yields:

$$C_{Operating} = (C_{labor} + C_{maint} + C_{chem} + C_{elect} + C_{water} + C_{waste} + C_{payovh} + C_{pltovh} + C_{tax})C_{idx} \tag{55}$$

The total cost per dry ton of cleaned coal is then found by adding Equations 22, 45, and 55 to the raw coal cost:

$$C_{Total} = C_{Raw} + C_{Refuse} + C_{Capital} + C_{Operating} \tag{56}$$

To express total coal cost on a wet (as-delivered) basis, Equation 56 would be multiplied by one minus the coal moisture content.

Illustrative Examples

Figure 4 shows examples of model results, displaying the change in total cleaned coal cost as a function of the reduction in normalized sulfur content for three different coals, each "washed" in three assumed plant configurations (Levels 2, 3, 4). For any given plant level, the total cost increases non-linearly with increasing sulfur reduction, due primarily to the increase in coal refuse cost as the plant yield is decreased to obtain higher sulfur removal. For each coal, the most economical plant design level is seen to depend on the desired degree of sulfur removal. For the cases in Figure 4, a Level 2 or 3 plant is preferred except at very high reduction levels where a Level 4 plant is superior. In general, however, sulfur reductions in excess of 30% are not likely to be economical for steam coal applications.[10,13]

The computer program used to derive these results can be operated in a stand-alone fashion or coupled with other emission reduction process models. For each plant stream, the optimum mass and energy process yields, specific gravity of separation, and resulting cleaned coal characteristics are reported, along with the percent changes in coal quality and a breakdown of total washed coal costs showing the contributions of capital charges, operating costs, and coal refuse. A detailed numerical example of model calculations and results appears in Reference 10.

Concluding Discussion

The analytical model described here provides a method of estimating the properties and cost of coals washed for sulfur and/or ash reduction to help meet emissions and coal quality constraints. Because detailed data requirements are kept to a minimum, the model can readily be used for preliminary design studies and technical assessments, where it offers a number of significant improvements over methods previously used for such purposes. In comparison to detailed engineering design models for coal preparation plants, the cost predicted here are generally comparable for similar design assumptions. For example, only a 4 percent difference in annualized plant cost was founded for a Level 3 plant design using a detailed costing method recently developed for the Electric Power Research Institute.[14] Differences in total cleaned coals cost were even smaller (0.4 percent) when the cost of refuse coal also was considered.

When used in conjunction with a comprehensive database of coal washability characteristics[7] the preparation plant model described in this paper provides a building block for the development of statistical regression models for estimating washed coal properties and cost on a regional basis.[15] When incorporated into larger simulation models of the coal and electric utility sectors,[2,13] this offers the capability of assessing the economic potential of coal washing in conjunction with other available measures of achieving air pollution emission standards. The coal cleaning plant model also has

been coupled with models of combustion and post-combustion methods of pollutant removal to provide a framework for analying integrated environmental control options on a site-specific basis.[10,16]

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